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6. AUTHOR(S)  Steven L. Garrett					
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13. ABSTRACT (Maximum 200 words)  The purpose of this research project is to study the fundamental physical processes which are involved in production of high cooling powers from electrically driven thermoacoustic refrigerators. The results of these experimental investigations are then utilized to produce improved designs for the next generation of high-power thermoacoustic refrigerators, chillers, and air-conditioners.  These research objectives are achieved by an integrated combination of experimental measurements on thermoacoustic components and subsystems, as well as complete refrigeration systems. Comparison of the measured performance to analytic models based on differential equations (low amplitude) and similtude (high amplitude) and to numerical models based on the Los Alamos National Laboratory Design Environment for Low-Amplitude ThermoAcoustic Engines (DELTA-E), are then made.					
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# High Power ThermoAcoustic Refrigeration

## ANNUAL SUMMARY REPORT (01 June 1995 - 31 May 1996)

Submitted by:  
Steven L. Garrett  
United Technologies Corporation Professor of Acoustics  
Graduate Program in Acoustics  
Penn State University  
State College, PA 16804

Submitted to:  
Office of Naval Research  
800 N. Quincy Street  
Arlington, VA 22217

June 1996

### I. Description of Project

The purpose of this research project is to study the fundamental physical processes which are involved in production of high cooling powers from electrically driven thermoacoustic refrigerators. The results of these experimental investigations are then utilized to produce improved designs for the next generation of high-power thermoacoustic refrigerators.

### II. Description of Approaches

The objectives of this research are achieved by an integrated combination of experimental measurements on thermoacoustic components and subsystems, as well as complete refrigeration systems, and comparison of the measured results to analytic models based on differential equations (low amplitude) and similitude (high amplitude) and on numerical models based on the Los Alamos Design Environment for Low-Amplitude ThermoAcoustic Engines (DELTA-E). The emphasis of our approach is on laboratory measurements. We have found that the challenges which are created in the laboratory by the limitations of the present-day hardware have historically been the most fruitful means for stimulating invention of the improvements that will be implemented in the next generation of thermoacoustic refrigeration systems.

To accelerate progress in our understanding of high power thermoacoustic heat transport, we will use three existing refrigerators: two Space ThermoAcoustic Refrigerators (STARs) and the Shipboard Electronic ThermoAcoustic Cooler (SETAC), and the four high-power (100 Watt<sub>acoustic</sub>) SETAC electrodynamic drivers. Modifications of these refrigerators will be used to examine the acoustic and thermal performance of new and existing thermoacoustic components at high powers than were previously possible. We will also continue to measure the performance alternative refrigerator geometries such as the existing torsionally resonant Toroidal ThermoAcoustic Refrigerator (T-TAR).

### III. Accomplishments During this Report Period

*Laboratory Relocation.* The primary accomplishment, during this reporting period, has been the relocation of the laboratory from the Naval Postgraduate School (NPS) in Monterey, CA, to the Applied Research Laboratory (ARL) at Penn State University in State College, PA. This relocation provided a substantial increase in the quantity and quality of laboratory space as well as providing improved access to research-related services including machine shops, custom electronics fabrication facilities and other support facilities and staff. These improvements were required to allow fabrication and testing of thermoacoustic refrigeration systems with cooling capacities in excess of 1000 Watt<sub>thermal</sub>.

The transfer of the laboratory instrumentation required extensive administrative interactions involving the Physics Department and Property Management Division at NPS, the Chicago District Office of Naval Research (ONR), and ARL. By the end of this reporting period, almost all of the thermoacoustic research instrumentation, as well as the STAR and SETAC refrigerators and their support systems, have been moved to ARL. The equipment which had to remain at NPS to support other investigators has been replaced using supplemental funds provided by ONR.

*High Power Drivers.* A new electrical driver has been identified which uses a moving magnet (instead of moving coil) to produce high amplitude standing acoustic waves. Various versions of these drivers have been fabricated as alternators which convert mechanical to electrical energy at power levels up to 10 kW<sub>electrical</sub> with electromechanical efficiencies as high as 90%. During the next year, we will attempt to convert these alternators to drivers and test their performance in thermoacoustic refrigerators. Research was also begun on high power piezoelectric and electrostrictive driver mechanisms as well as a novel magnetohydrodynamic driver which uses oscillatory magnetic fields to drive resonances in ferrofluids.

*Resonator Designs.* Several high power, multiple-stack thermoacoustic design concepts were considered. No progress has yet been made in attempting to determine the optimum geometry and operating parameters (pressure, gas mixture, stack geometry and spacing, etc.), since those choices will depend on the results of high-power component tests in the existing STAR and SETAC systems.

*Vibro-centrifugal Pumps.* Due to the absence of laboratory instrumentation, only one preliminary experiment has been completed during this reporting period. Reh-lin Chen demonstrated that liquid could be pumped centrifugally by a tube which was attached to a bar vibrating in its first flexural mode. The bar was rigidly clamped at one end and free at the other end. This acoustical pumping process is intended to circulate hot and cold heat exchange fluids in the high-power torsionally resonant toroidal thermoacoustic refrigerator (US Navy Patent Case No. 77521). If successful, this could remove the necessity to provide separate pump motors for thermoacoustic refrigeration systems.

*Thermoacoustic Education.* The first full-semester (16 week) course on thermoacoustics, ACS 597C, was offered at Penn State from August through December, 1995. In addition to its coverage of the fundamentals of thermoacoustic heat transport (thermodynamics, kinetic theory of gas mixtures, hydrodynamics and similitude), lectures and problem sets were included on topics related to thermoacoustic engine component development. These topics include electrodynamic driver and bellows design, heat exchanger design, data analysis, thermoviscous loss mechanisms and resonator design for shock wave suppression. Copies of the problem sets for the course are included as Appendix A. Negotiations with two publishers are currently in progress with the goal of producing a textbook based on these lectures and problem sets over the next two years.

#### IV. Graduate Students

In addition to the PI, the thermoacoustics research group currently includes three graduate students which were supported by the Grant during this reporting period. All three of those students were enrolled in the initial offering of ACS 597C - Thermoacoustics, and all three students received an "A" grade in the course.

*Matt Poese* is a first-year graduate student who has been in the thermoacoustics research group since he arrived at Penn State in August, 1995. He received his BS degree in Mechanical Engineering. In addition to his excellent undergraduate record, Matt has extensive industrial experience in modeling and control of the vibration of machine tools using modal analysis and with noise and vibration control while participating in a foreign work/study internship at the BMW plant in München.

Matt has had an excellent start to his graduate career. He was the only first-year student to take and pass the Candidacy Exam. He was selected as the Outstanding First-Year Student (First Place) by the local chapter of the Acoustical Society of America, and he was one of only ten students within the University to be selected for the two-year (\$10,000) NASA Space Grant Fellowship.

*Anat Grant* is a first-year graduate student who has been in the thermoacoustics research group since she arrived at Penn State in July, 1995. She received her BS degree in Mechanical Engineering. In addition to her excellent undergraduate record, Anat received a Summer Student Fellowship from Woods Hole Oceanographic Institution and worked as an Engineering Aide in the Research & Development group at ABB Combustion Engineering Power Plant Laboratories. Prior to entering graduate school, she also worked for three years at Purus Inc., a San José, CA, start-up company engaged in the manufacture and installation of volatile organic compound treatment equipment.

Anat was selected as the Outstanding First-Year Student (Second Place) by the local chapter of the Acoustical Society of America. She received a three-year Engineering Dean's Fellowship (\$15,000) when she started her graduate studies at Penn State.

*Reh-lin Chen* is a third-year graduate student who joined the thermoacoustics research group in February, 1996. Prior to joining the group, he worked with Prof. V. W. Sparrow on computational acoustics. His Master's thesis is entitled, "Time Averaged Pressure Distributions for Finite Amplitude Standing Waves."

OFFICE OF NAVAL RESEARCH  
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT  
for  
01 June 95 through 31 May 96

Contract/Grant Number: N00014-96-1-0049

Principal Investigator: Steven L. Garrett

Mailing Address with ZIP+4 if applicable: Graduate Program in Acoustics  
Penn State University  
P.O. Box 30  
State College, PA 16804-0030

Phone Number: (814) 863-6373

Facsimile Number: (814) 865-3119

E-mail Address: garrett@sabine.acs.psu.edu

a. Number of papers submitted to refereed journals but not yet published:	<u>2</u>
b. Number of papers published in refereed journals (ATTACH LIST):	<u>0</u>
c. Number of books or chapters submitted but not yet published:	<u>0</u>
d. Number of books or chapters published (ATTACH LIST):	<u>0</u>
e. Number of printed technical reports & non-refereed papers (ATTACH LIST):	<u>3</u>
f. Number of patents filed:	<u>2</u>
g. Number of patents granted (ATTACH LIST):	<u>0</u>
h. Number of invited presentations at workshops or professional society meetings:	<u>2</u>
i. Number of contributed presentations at workshops or professional society meetings:	<u>2</u>
j. Honors/awards/prizes for contract/grant employees, such as scientific society and faculty awards/offices (ATTACH LIST):	<u>4</u>
k. Number of graduate students supported at least 25% this year this contract/grant:	<u>3</u>
l. Number of post docs supported at least 25% this year this contract/grant:	<u>0</u>

How many of each are females or minorities? These six numbers are for ONR's EEO/Minority Reports. Minorities include Blacks, Aleuts, Amindians, etc., and those of Hispanic or Asian extraction/nationality. The Asians are singled out to facilitate meeting reporting semantics re "underrepresented".

Graduate student FEMALE: 1

Post doc FEMALE: 0

Graduate student MINORITY: 0

Post doc MINORITY: 0

Graduate student ASIAN E/N: 1

Post doc ASIAN E/N: 0

OFFICE OF NAVAL RESEARCH  
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT  
[01 June 1995 through 31 May 1996]

High Power ThermoAcoustic Refrigeration

a. Papers submitted to refereed journals but not yet published: Two

1. S. L. Garrett, "ThermoAcoustic Refrigerator," *NASA Technical Briefs*, in press.
2. A. Gopinath and S. L. Garrett, "Thermoacoustic Streaming in a Resonant Channel: the Time-Averaged Temperature Distribution," submitted to *J. Acoust. Soc. Am.*

b. Papers published in referred journals: None

c. Books or chapters submitted but not yet published: None

d. Books or chapters published: None

e. Printed technical reports & non-refereed papers: Three

1. Stephen C. Ballister and Dennis J. McKelvey, "Shipboard Electronics ThermoAcoustic Cooler," Master's Thesis, Applied Physics and Engineering Acoustics, Naval Postgraduate School, June, 1995. (This was also the final report for the Navy Science Assistance Program Task R-6-94).
2. Joseph W. Osborne, "Toroidal Thermoacoustic Refrigerator," Master's Thesis, Applied Physics and Engineering, Naval Postgraduate School, September, 1995.
3. S. L. Garrett and G. W. Swift, "Thermoacoustic refrigeration and its relationship to the Stirling cycle," *Proc. 7<sup>th</sup> Int. Conf. on Stirling Cycle Machines*, pp. 23-28 (1995). [See Appendix B]

f. Patents filed: Two

1. S. L. Garrett, "High Power Thermoacoustic Refrigerator," U. S. Patent Application, disclosed 30 June 95, U. S. Navy Case #77139, Registration Serial No. 08/520974.
2. S. L. Garrett, "Torsionally Resonant, Toroidal ThermoAcoustic Refrigerator," U. S. Patent Application, disclosed 15 Dec 95, U. S. Navy Case #77521.

g. Patents granted: None

h. Invited presentations at workshops or professional society meetings: Two

1. S. L. Garrett and G. W. Swift, "Thermoacoustic Refrigeration and its Relationship to the Stirling Cycle," 7<sup>th</sup> International Conference on Stirling Cycle Machines, Tokyo, Japan, 2-9 November 1995.
2. S. L. Garrett, "ThermoAcoustic Refrigeration," 1995 IEEE Ultrasonics Symposium, Seattle, WA, 9-10 November 1995.

i. Contributed presentations at workshops or professional society meetings: Two

1. D. McKelvey, S. Ballister and S. Garrett, "Shipboard Electronics Thermoacoustic Cooler," J. Acoust. Soc. Am. **98**(5), Pt. 2, 2961 (1995). [See Appendix C]
2. S. Garrett, "Hot Topics in Engineering Acoustics," J. Acoust. Soc. Am. **99**(4), Pt. 2, 2527 (1996).

j. Honors/awards/prizes for grant employees: Four

1. Anat Grant, Engineering Dean's Fellowship (\$15,000), Penn State University.
2. Matt Poesse, NASA Space Grant Fellowship (\$10,000), Penn State University.
3. Matt Poesse, Outstanding First-Year Graduate Student in Acoustics (First Place), Penn State Chapter, Acoustical Society of America.
4. Anat Grant, Outstanding First-Year Graduate Student in Acoustics (Second Place), Penn State Chapter, Acoustical Society of America.

k. Number of graduate students supported at least 25% this year of the grant: Three

1. Matt Poesse
2. Anat Grant
3. Reh-lin Chen

l. Number of post docs supported at least 25% this year of the grant: None



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High Power ThermoAcoustic Refrigeration  
[UNDER GRANT PE 61153 N00014-96-1-0049]

ANNUAL SUMMARY REPORT

DR LOGAN E. HARGROVE ONR 331  
OFFICE OF NAVAL RESEARCH  
800 NORTH QUINCY STREET  
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ADMINISTRATIVE GRANTS OFFICER  
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ATTN GERALD T. SMITH  
OFFICE OF NAVAL RESEARCH  
CHICAGO REGIONAL OFFICE  
FEDERAL BUILDING ROOM 208  
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CHICAGO IL 60605-1588

PROFESSOR W PATRICK ARNOTT  
ATMOSPHERIC SCIENCES CENTER  
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RENO NV 89506

PROFESSOR A A ATCHLEY  
PHYSICS DEPT CODE PH/AY  
NAVAL POSTGRADUATE SCHOOL  
MONTEREY CA 93943

PROFESSOR H E BASS  
DEPARTMENT OF PHYSICS AND ASTRONOMY  
UNIVERSITY OF MISSISSIPPI  
UNIVERSITY MS 38677

DR KEITH GILLIS  
THERMOPHYSICS DIVISION  
NATIONAL INSTUTE OF STANDARDS AND TECHNOLOGY  
GAITHERSBURG MD 20899-0001

PROFESSOR R M KEOLIAN  
PHYSICS DEPT. CODE PH/KN  
NAVAL POSTGRADUATE SCHOOL  
MONTEREY CA 93943

PROFESSOR MOISES LEVY  
DEPARTMENT OF PHYSICS  
UNIVERSITY OF WISCONSIN MILWAUKEE  
MILWAUKEE WI 53201

PROFESSOR P L MARSTON  
DEPARTMENT OF PHYSICS  
WASHINGTON STATE UNIVERSITY  
PULLMAN WA 99164-2814

PROFESSOR R E PACKARD  
PHYSICS DEPARTMENT  
UNIVERSITY OF CALIFORNIA  
BERKELEY CA 94720

PROFESSOR A PROSPERETTI  
DEPARTMENT OF MECHANICAL ENGINEERING  
JOHNS HOPKINS UNIVERSITY  
BALTIMORE MD 21218

PROFESSOR R RASPET  
DEPARTMENT OF PHYSICS AND ASTRONOMY  
UNIVERSITY OF MISSISSIPPI  
UNIVERSITY MS 38677

PROFESSOR O G SYMKO  
DEPARTMENT OF PHYSICS  
UNIVERSITY OF UTAH  
SALT LAKE CITY UT 84112